Leaky Fields from Damaged Shields

Brian A. Jones, *Student Member¸IEEE,* Cynthia Furse, *Fellow¸IEEE*
Department of Electrical and Computer Engineering
University of Utah
Salt Lake City, USA

I. Introduction

In a world where wireless devices appear to dominate society, it is wires that truly rule and connect our lives. Certainly the spread of cellular phones, Bluetooth technology, wireless sensor networks, and advances of ion-lithium battery capabilities have made common daily devices more disconnected and portable. However; at the end of the day we are reaching for wired chargers for power, transporting ourselves around in planes and car with extensive wiring, and living in homes still very connected with wires.

Physical wiring has well known problems that affect performance and sometimes safety. Wiring faults in buildings and home can lead to electrical fires. Aging aircraft wiring contributes to system malfunctions that can lead to fatal crashes [1]. The type of damage varies from simple cracks and small shield damages to frays and severed cables. Simple bends and kinks in RF cables lead to degradation and poor performance at higher frequencies. Although systems may perform well for years, eventually age and normal physical wear naturally lead to wire problems. The detection, location, and identification of wire faults are a large area of research and investigation.

Research and development in the area of wire fault detection has been approached from many different angles. Features relevant to the problem can be extracted from time domain, frequency domain, or time-frequency domain data [2]. Techniques from the basic visual inspection to advanced neural networks, Kalman filters, etc. each provide a level of effectiveness, but also have drawbacks [2]. With the varying degree of wire faults that exists it is no surprise that varying methods are needed to map the entire fault space. There is no single method effective in all fault cases.

The problem of small wire faults in cable shields is addressed in this paper. Small faults such as damage to the shield are very difficult to detect. Common tools such as time-domain reflectometry may not be able to distinguish a reflection from a small fault hidden in the noise. Damage to the shield has the potential of being seen from the outside of the cable; perhaps not visually due to the size of the damage, but electrically. Electromagnetic fields escape through small cracks or holes in the shield. We would like to use these external fields to diagnose the faults in the shield. This paper evaluates if those fields are detectable and how to detect them.

The detection, location, and identification of wire faults is a serious problem. According to a previous Air Force Research Laboratory study on Air Force mishaps, 43% of mishaps related to electrical systems are due to connectors and wiring [3].

Reflectometry is a common method of fault detection and location [4]. These methods send a low-voltage high-frequency signal down the wire and detect reflections from anomalies along the length of the wire. These methods are presently available for detecting open and short circuits, but frays or chafes and other small damage are more difficult to detect. Reflectometry comes in multiple flavors., depending on the type of signal sent down the wire. Time domain reflectometry (TDR) uses a step function or pulse [4]-[6], frequency domain reflectometry (FDR) uses a set of sine waves [7], spread spectrum time domain reflectometry (SSTDR) uses a pseudo-noise (PN) code or sine wave modulated PN code [8], and others [4]. The short coming of all reflectometry methods is that reflections from small faults are very small, and therefore get lost in the noise.

System modeling is used to calculate the reflectometry response from a fault in a specific system. When a fault or fray is introduced into a wire, the impedance changes at the fault location. Many types of faults on unshielded wires have been simulated. [9]-[11] This information helps quantify what effects will be seen in a system when faults are introduced. With this information detection systems can be better design as the various types of faults are simulates and modeled.

Using advanced modeling of faults, preventative methods have been investigated to allow early warning or detection of faults. Prognostic health management (PHM) [12]-[14] and location of intermittent arc faults [15] are two of these proactive applications. Signal processing techniques such a wavelets [16], deconvolution, matched-filters, de-noising, and Bayesian techniques have also been applied to provide better detection and location of wire faults.

Previous research and development has produced systems that are capable of locating large faults on cables, but locating the smaller faults has been elusive and minimally effective at best. This is partly because previous studies have been limited to unshielded cables. These cables thwart attempts to locate small faults, because normal impedance variation caused by vibration or condensation on the wires is as large or larger than impedance changes caused my chafes or frays. In this paper we will focus on shielded cables. The grounded shields significantly reduce the impedance changes caused by the vibrating vehicular environment, thus enabling detection and location of much smaller faults. There are two ways this could be done. One is evaluating the reflectometry response on the quieter, shielded cable. This is possible, but we are still looking for a small reflection amongst larger induced signals on the wire. The other method, which we will focus on in this paper, is investigating the fields that leak from the fault onto the outside of the shield. These signals are small, indeed, but they should be zero. In this case we are looking for a small signal where there should be none, rather than a small signal amidst larger signals. This requires a test system with less dynamic range, and provides a potentially viable test method for small faults in cable shields. A basic cable model is introduced in section II, and section III discusses a simple pickup sensor idea with initial simulations and measurements.

II. SIMULATION OF FIELDS EXTERNAL TO A CABLE

Determining the fields on the outside of the cable due to a fault in the shield will involve a process of simulation and lab measurements. The type of wiring we are going to focus on in this paper is the standard coax cable, although the concepts can be extended to twisted shielded pair (TSP) and other shielded cable types. The question we are most interested in is what fields propagate from the inside to the outside of the cable when there is a hole in the shield

Bethe developed rigorous mathematical expressions to describe fields leaking through a small hole between two cavities [17]. Bethe's theory was applied to waveguides and validated by additional studies [18]-[19]. Two waveguides were placed parallel to each other with a small hole connecting the two. Fields were shown to leak into the adjoining waveguide through the small hole. Applying the theory to coax cables, if a signal is travelling down the cable and there is a small hole in the shield, then some fields could be leaking out and may be detectable on the outside of the shield.

To better understand the fields outside a damaged coax shield we used a 3D model of RG-58 coax simulated using the Computer Simulation Technology (CST) software with the Microwave Studio (MWS) suite. Table I gives the parameters for the RG-58 coax shown in Figure 1. Each end of the coax is terminated with an (impedance matched) CST waveguide port. The waveguide port represents an infinitely long waveguide connected to the structure. A waveguide port stimulates and absorbs energy with very low loss reflections. A simulation was run using a Gaussian pulse as the excitation signal. Later work will consider more detailed pulse and signal shapes representing other reflectometry systems.

The field patterns from the basic RG-58 cable without any damage were zero on the outside of the cable as expected. Next we simulated a hole in the coax cable by subtracting out a cylinder shape from the middle of the model. Figure 2 shows the fields internal and external to a coax cable with a cylindrical hole at the center of the cable. The hole penetrates the shield and part of the interior dielectric. If the hole is small enough that it does not penetrate the shield (damage to the outer insulation only), no fields escape from the cable. Figure 2 illustrates the fields at the hole with a cross-section view of the coax cable. The electric fields can be seen escaping through the hole.

Visually these simulations indicated signals on the outside of the cable that are propagating towards both ends of the cable. These signals could potentially be picked up by a probe on the outside of the wire.

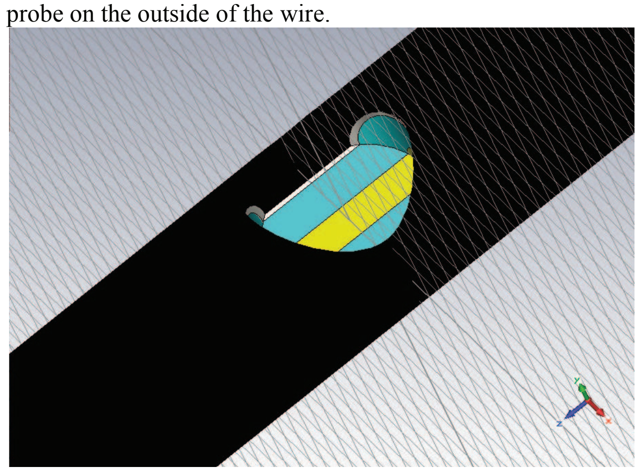

Figure 1 RG-58 cable modeled in CST

Their mere presence indicates a hole. The phase shift between the incident signal on the wire and that received from outside through the hole may be able to tell us the location of the hole. The magnitude and / or frequency spectra of these signals may be able to tell us the size and nature of the hole. These rudimentary simulations provide motivation to continue research and modeling of small faults to aid in the study of the external fields. Improvements to the model to more accurately reflect shield damage, size, signal excitation, and expressions to describe these external fields will be presented at the conference.

III. USING A COIL RECEIVER TECHNIQUE

With a simple model of an RG-58 coax cable established we turn our attention to detecting the external fields. One approach utilizes a coil (toroid) sensor. The coax cable goes through the center of the coil, and measurement devices connected to the coil receive signals. The following subsections present a simulation and initial lab results from such a setup.

A. Simulation

A simplistic CST model was simulated using a basic coil. Building upon the RG-58 coax model already developed, a ferrite coil was added as illustrated in Figure 3. This model was simulated with the same parameters defined earlier in the paper. The signals received by the coil are shown in Figure 4. They are very small, and they are the derivative of the (Gaussian pulse) signal on the wire. Multiple reflections are also seen, because of mismatches within the coil system.

TABLE I. RG58 MODEL DEFINITION

Parameter	Material	Diameter inches (mm)	Electrical Properties
Conductor	Copper	0.032 (0.8128)	Std. Copper
Dielectric	Low Density Cellular Polyethylene (LPDE)	0.116 (2.9464)	$\varepsilon_r = 2.4$
Shield	PEC	0.138 (3.5052)	PEC
Jacket	Polyvinylchloride (PVC)	0.195 (4.953)	$\varepsilon_r = 3.4$

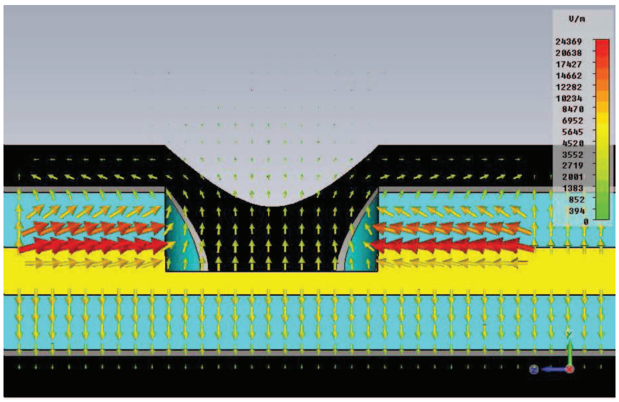

Figure 2 Coax cross-section at the middle of the cable, showin electric fields escaping from the hole

Although this CST model is fairly basic, the result helps motivate the additional research and study needed to better understand the fields leaking outside the cable and the potential use of a coil sensor. The downside of this CST simulation is the incredibly small response of the signal, on the order of 10^{-7} V for a 1 V input signal. It will be very difficult to measure and capture these signals. As the coil moves away from being centered over the hole the signals are even smaller and more difficult to detect. Still, our simple measurement system has been able to detect the faults.

B. Experimental Measurements

The previous section provides motivation that measureable fields exist on the outside of the cable. A few questions quickly arise; how far do the fields extend, how large are the fields, and perhaps most importantly can the fields be detected in practice? We know that small faults are difficult to detect with common TDR measurements, because the reflected signal becomes lost in the noise. One advantage to the detection of holes in the shield is that these types of faults are NOT intermittent. That means we can look for them in relative leisure when the aircraft is on the ground, in a quiet environment with no other signals (other than environmental noise) on the cables being tested.

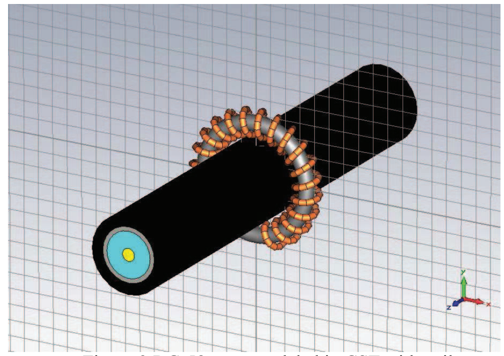

Figure 3 RG-58 coax modeled in CST with coil sensor.

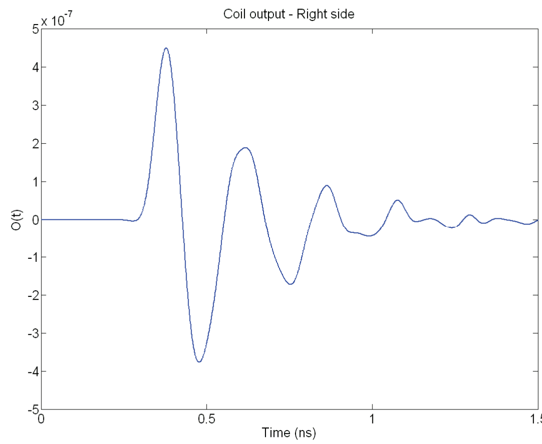

Figure 4 Coil output signal when located at the center of the coax directly over hole.

In order to test the coil sensor idea simulated in the previous section, a lab experiment shown in Figure 5 was set up. A coil of copper wire was hand wound around a ferrite core to create a toroid and attached to port 2 of the network analyzer via an RG-58 cable. A 30' RG-58 cable was connected to port 1 and run through the center of the toroid.

The experiment was executed in two steps. During the first step measurements were taken with no damage to the shield. The response from the ferrite coil alone is show in Figure 6. Data collected from the network analyzer was in the frequency domain. A simple inverse Fourier transform was used to convert it to the time domain.

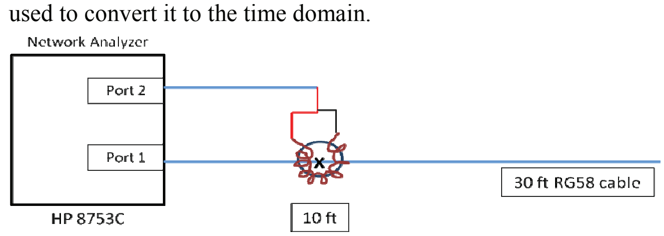

Figure 5 Test setup for coil sensor experiment

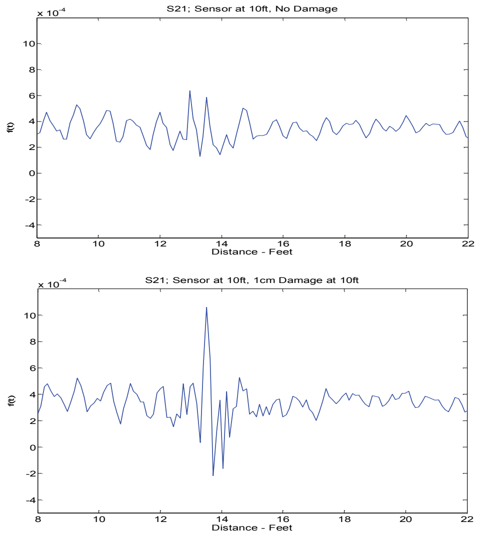

Figure 6 Measurement before shield damage (top) . Measurement after shield damage (bottom).

The second part of the test is to damage the shield (using an xacto knife in this case) and retake the measurement. A 1-cm chafe was made on the shield 10ft from port 1. Measurements in the frequency domain were Fourier transformed to give the time domain response shown in Figure 6. The graph shows a distinct spike caused by the signal leaking out of the cable and being received by the toroid. The spike is not centered around 10ft, however, because the signal leaves port 1, travels 10 feet down the cable, out of the hole, is picked up by the sensor, and travels a few feet back through port 2. We are still working out the details of the various velocities of propagation (inside and outside of the cable are different), and the nature of the external signal, to be able to use the measured signature to determine the location of the fault.

IV. CONCLUSION

Initial simulations and lab measurements were presented in this paper regarding leaky fields from small holes. Computer simulations provided motivation that external fields could be sensed by a rudimentary coil sensor. Lab experiments provided initial data that these external signals are detectable. The work going forward will focus on quantifying the effect of shield damage size and shape to leaky fields, the strength of the fields as the coil moves away, and optimal coil sensor design.

ACKNOWLEDGMENT

This work was supported by the Air Force Research Labs via a grant from the Universal Technology Corporation.

REFERENCES

[1] C. M. Furse and R. Haupt, "Down to the wire: The hidden hazard of aging aircraft wiring," *IEEE Spectrum*, vol.38, pp.34-39, Feb 2001.

[2] G. Liu, Y.N. Cao, and Y. Liu, "A Survey on Arc Fault Detection and Wire Fault Location for Aircraft Wiring System," *SAE International Journal of Aerospace*, Vol. 1, pp. 903-914, 2009.

[3] G.A Slenski, Aircraft Wiring System Integrity Initiatives – A Government and Industry Partnership," *The Journal of the Reliability Analysis Center*, Second Quarter, pp. 10-12, 2002.

[4] L.A. Griffiths, R. Parakh, C. Furse, and B. Baker, "The Invisible Fray: A Critical Analysis of the Use of Reflectometry for Fray Location", *IEEE Sensors*, pp. 697-706, Vol. 6, June 2006.

[5] A. Lelong, and M.O. Carrion, "On Line Wire Diagnosis using Multicarrier Time Domain Reflectometry for Fault Location", *IEEE Sensors*, pp. 751-753, Vol. 9, October 2009.

[6] C. Hsue, and T. Pan, "Reconstruction of nonuniform transmission lines from time-domain reflectometry," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 45, pp. 32-38, January 1997.

[7] C. M. Furse, You Chung Chung, R. Dangol, M. Nielsen, G. Mabey, and R. Woodward," Frequency-domain reflectometry for on-board testing of aging aircraft wiring," *IEEE Transactions on Electromagnetic Compatibility*, vol. 45, pp.306-315, May 2003.

[8] C. Furse, P. Smith, M. Safavi, and C. Lo, "Feasibility of spread spectrum reflectometry for location of arcs on live wires," *IEEE Sensors Journal*, pp.1445-1450, December 2005.

[9] S. Arunachalam, and B. Diong, "A Parametric Model Approach to Arc Fault Detection for DC and AC Power Systems," *Industry Applications Conference, 41st IAS Annual Meeting,* pp. 2249 – 2255, October 2006.

[10] H. Zang, T. Chen, and W. Li, "Arc Fault Signatures Detection on Aircraft Wiring System", The Sixth World Congress on Intelligent Control and Automation, pp. 5548-5552, October 2006.

[11] W. Yongxing, D. Enyuan, C. Jiyuan, Z. Jiyan, and D. Koenig, "Arc Tracking Properties of the Aging Wires in Aircraft", *2nd International Symposium on Systems and Control in Aerospace and Astronautics*, pp. 1-5, February 2009.

[12] K. Keller, K. Swearingen, and J. Sheahan, "Aircraft Electrical Power Systems Prognostics and Health Management," *IEEE Aerospace Conference*, pp. 1-12, July 2006.

[13] M. Pecht, "Prognostics and Health Monitoring of Electronics", *International Conference on Electronic Materials and Packaging*, pp. 1-10, December 2006.

[14] J. Hannu, D. Kolstov, Z. Xu, A. Richardson, and M. Moilanen, "An Embedded Test & Health Monitoring Strategy for Detecting and Locating Faults in Aerospace Bus Systems," *Informal proceedings of the IEEE European Test Symposium*, Italy 2008.

[15] A. Ukil, and R. Zivanovic, "Abrupt change detection in power system fault analysis using adaptive whitening filter and wavelet transform", *Electric Power Systems Research*, Vol. 76 , pp. 815–823, 2006

[16] C. Desai, K. Brown, M. Desmulliez, and A. Sutherland, "Selection of Wavelet for De-noising PD waveforms for Prognostics and Diagnostics of Aircraft Wiring," *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 17-20, 2008.

[17] H. A. Bethe, "Theory of Diffraction by Small holes", *The Physical Review*, Vol. 66, No. 7, pp. 163-182, October 1944.

[18] C. Peterson-Espino, J. Mahon, and P. Macdonald, "Scattering from a Small Hole: Verification of Collin's Predictions from Bethe's Theory", *IEEE Antennas and Propagation Society International Symposium,* Vol. 3, pp. 2064-2067, July 1997

[19] C. Peterson, "A Rigorous Analysis of Rectangular Apertures in Rectangular Waveguides", PhD. Dissertation, UCLA, 1995.

[20] S. Tumanski, "Induction coil sensors—a review", *Measurement Science and Technology*, Vol. 18, pp. 31-46, January 2007.